MISSION INNOVATION

accelerating the clean energy revolution

MI INNOVATION CHALLENGES

Impact Report

September 2020

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About this Report

This report was produced by Mission Innovation's Analysis and Joint Research (AJR) Sub-group. Canada, as one of the co-leads of AJR, was the lead author with input from the MI Secretariat and Innovation Challenge co-leads in Australia, Brazil, Canada, China, the European Commission, France, Germany, India, Italy, Saudi Arabia, and the United Kingdom.

Abbreviations

ACT	Accelerating CCS Technologies
AJR	Analysis and Joint Research
CCB	Comfort and Climate Box
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization and storage
CEM	Clean Energy Ministerial
GCP	Global Cooling Prize
IC	Innovation Challenge
IEA	International Energy Agency
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
IRENA	International Renewable Energy Agency
ISGAN	International Smart Grid Action Network
MAP	Materials acceleration platform
MI	Mission Innovation
MI-3	Third Mission Innovation Ministerial
MI-4	Fourth Mission Innovation Ministerial
PRD	Priority research direction
R&D / RD&D	Research and development / Research, development and demonstration
RMI	Rocky Mountain Institute
SGIA	Smart Grids Innovation Accelerator
TCP	Technology Collaboration Programme
TES	Thermal energy storage
TRL	Technology readiness level
WEF	World Economic Forum

Introduction

At COP22 in 2016, Mission Innovation (MI) members came together to endorse seven Innovation Challenges (ICs) aimed at catalyzing global collaboration on clean energy research, development and demonstration (RD&D). In May 2018, at the Third Mission Innovation Ministerial (MI-3), MI members endorsed an eighth Innovation Challenge on Renewable and Clean Hydrogen.

As MI nears the end of its initial five-year mandate (in June 2021), the MI Steering Committee (MISC) asked the Analysis and Joint Research Sub-group to assess the outcomes and impacts of the ICs since December 2016. This report summarizes how the eight Innovation Challenges have supported MI's mission to "accelerate the pace of clean energy innovation."

Part 1 of this report provides an overview of the Innovation Challenge model and the Innovation Challenges themselves. Part 2 showcases three projects for each IC and summarizes how these projects have supported MI's goals. Note that this report does not contain an exhaustive list of all IC activities. Rather, this report seeks to highlight key projects led or coordinated by the ICs and to describe in detail what the outcomes of those efforts have been. Without the ICs, these projects would not have had the outcomes they did – and in many cases, the projects would not have happened outright. Part 3 reflects on the collective successes of the ICs. Mission Innovation can build on the achievements, networks, and recent momentum of the Innovation Challenges, as members look to amplify the impact of MI beyond 2020.

Background

A number of principles have shaped the development of the Innovation Challenges:

- *The ICs are intended to support, reinforce, and complement national RD&D activities* – Early on, MI recognized that members have diverse energy needs and innovation systems. Innovation Challenges were defined to address energy R&D issues of global importance, leveraging national capabilities while taking advantage of the benefits of international R&D collaboration.

- *The ICs are led by member countries* – Although ICs collaborate with external organizations to help advance objectives, it is the voluntary efforts of member countries that drive the work of each IC.

- *ICs adopt different approaches to meet their objectives* – AJR provides guidance and high-level coordination across the ICs; however, the priorities and activities of each IC are set and advanced by co-leads and members.

The objectives of each IC are outlined in Table 1. (For a full list of IC co-leads and members, refer to Annex 1).

Table 1 - Summary of objectives for each Innovation Challenge

IC1	Smart Grids	To enable future grids that are powered by affordable, reliable, decentralised renewable electricity systems.
IC2	Off-grid Access to Electricity	To develop systems that enable off-grid households and communities to access affordable and reliable renewable electricity.
IC3	Carbon Capture	To enable near-zero CO_2 emissions from power plants and carbon intensive industries.
IC4	Sustainable Biofuels	To develop ways to produce, at scale, widely affordable, advanced biofuels for transportation and industrial applications.
IC5	Converting Sunlight	To discover affordable ways to convert sunlight into storable solar fuels.
IC6	Clean Energy Materials	To accelerate the exploration, discovery and use of new high-performance, low-cost clean energy materials.
IC7	Affordable Heating & Cooling of Buildings	To make low-carbon heating and cooling affordable for everyone.
IC8	Renewable and Clean Hydrogen	To accelerate the development of a global hydrogen market by identifying and overcoming key technology barriers to the production, distribution, storage, and use of hydrogen at gigawatt scale.

Given that ICs work with different technologies and at different technology readiness levels (TRLs), the suite of activities they pursue – including their engagement efforts with industry and other stakeholders – is quite diverse. While ICs have taken different paths over the past four years, common IC activities have included:

- Defining objectives and priorities for the IC;
- Identifying critical innovation needs and opportunities for RD&D collaboration (e.g. through deep-dive workshops, technology roadmaps);
- Engaging industry stakeholders to identify business needs and opportunities for public-private collaboration;
- Convening the innovation community around critical RD&D topics and sharing research findings, lessons learned, and best practices;
- Funding RD&D projects (e.g. through joint funding calls, prize competitions); and
- Engaging other international organizations or coalitions to leverage expertise and strengthen delivery of initiatives.

ICs have mobilized in a relatively short period of time, relying on the leadership and voluntary efforts of members to advance IC objectives. Figure 1 illustrates key milestones in the history of the Innovation Challenges.

In the pages that follow, this report showcases three projects for each IC and describes how these projects have helped to advance MI's mission.

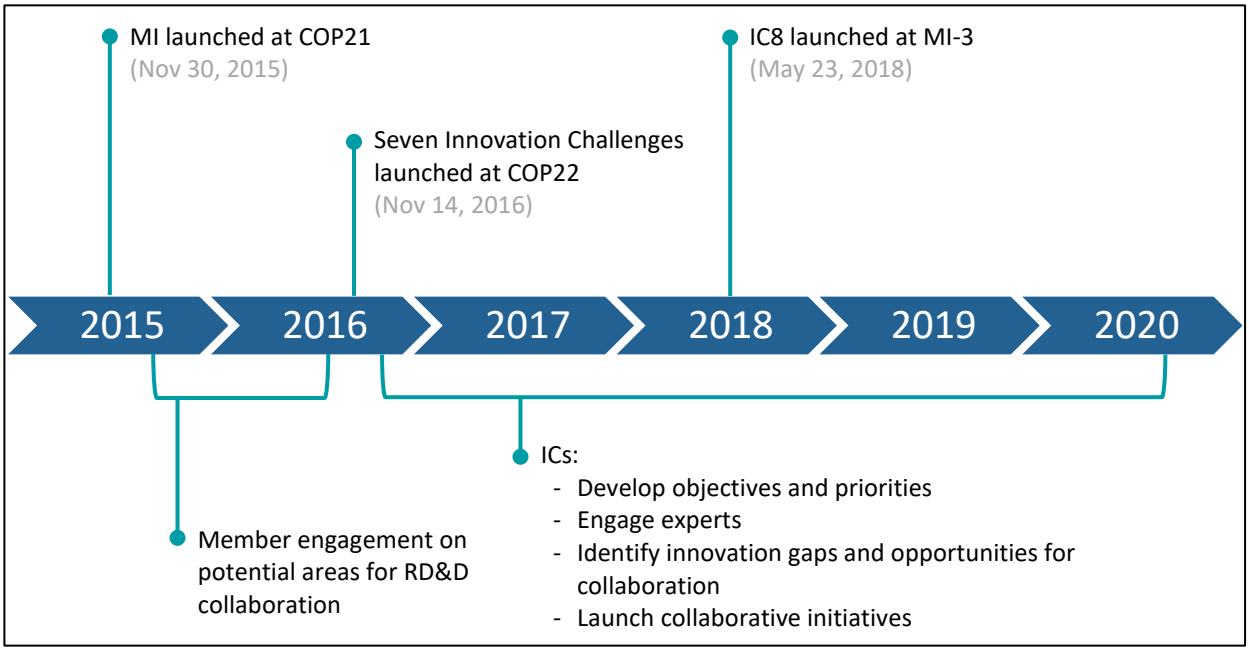

Figure 1 - Timeline of the Innovation Challenges

INNOVATION CHALLENGE #1 (IC1)

Smart Grids

About IC1

Objective: "To enable future grids that are powered by affordable, reliable, decentralised renewable electricity systems."

Co-leads: China, India, Italy

Participants: Australia, Austria, Brazil, Canada, Denmark, European Commission, Finland, France, Germany, Indonesia, Mexico, Netherlands, Norway, Republic of Korea, Saudi Arabia, Sweden, United Kingdom, United States

The integration of renewable energy sources and advanced technological solutions for power systems (e.g. storage, high voltage direct current connections, and smart meters) is an essential element for reducing global greenhouse gas emissions. However, the intermittent nature of variable renewable energy sources raises concerns about system stability and reliability. IC1 members are collaborating on smart grids and storage RD&D in order to accelerate the integration and optimization of smart grid technologies.[1]

Project #1: Funding Opportunities for Smart Grids

IC1 members have funded smart grid projects in line with jointly identified R&D priorities.

On a multilateral level, India is notably funding collaboration in smart grids R&D. India's "Smart and Resilient Networks" program is a five-year funding call (2018-2022) worth US$5.0 million that supports collaboration with academia, utilities, and industry on nine R&D projects. Nine IC1 members[2] are contributing knowledge and technical expertise to support this funding opportunity, along with the support of 20 international institutions, 17 national institutions, and 16 companies and utilities. Under this funding call, approximately:

- US$2.5 million has been invested to address the challenges in renewable energy generation and integration to conventional grid;
- US$1 million has been invested to develop the smart grids solutions for the transition from conventional to electric vehicles;
- US$1 million has been dedicated to facilitate financial and market strategies that support renewable generation; and
- US$0.5 million has been invested in addressing the challenges in cyber-physical systems in smart grids.

[1] IC1 has identified six R&D priority areas: (1) Storage Integration; (2) Demand Response; (3) Regional Electricity Highways; (4) Flexibility Options; (5) New Grids Control Architectures; and (6) Power Electronics.
[2] i.e. Australia, Canada, China, France, Germany, Italy, Norway, UK, and USA.

For example, the D-SIDES smart grids project aims to enhance distribution grid stability in the context of high penetration of photovoltaics and dynamic loads. D-SIDES has benefited from the participation and contributions of research organizations from India, Canada, China and Italy.

Individually, IC1 members also dedicate financial resources on a national level to support smart grids R&D. IC1 members come together to share best practices and lessons learned from their funding programs through workshops and IC1 reports (including the 2017 and 2019 IC1 Country Reports, which consolidate information about national energy strategies, trends, projects and innovation actions in the field of smart grids).

Project #2: IC1-led Workshops (including IC1-ISGAN Collaboration)

Since 2017, IC1 has convened the international smart grid community by organizing six international events[3], each consisting of a one-day public event and a two-day Deep-Dive workshop. The public events provided opportunities for Ministers and/or high-level ministry officials to confirm their countries' continued commitment to supporting collaboration within IC1. Moreover, keynote speakers from the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), World Economic Forum (WEF), national regulators, and the private sector shed light on global energy trends and challenges as well as opportunities for smart grids in modernizing and decarbonizing energy systems worldwide. IC1 also organized specific sessions and workshops with industry involvement, challenging IC1 members and the private sector to share ideas on how to accelerate the adoption of smart grids solutions worldwide. Supplemental to these public events, IC1 deep-dive workshops fostered collaboration among IC1 members and served as an opportunity to discuss future joint activities.

Notably, the 4th IC1 Deep-Dive Workshop in November 2018 (Rome) marked the beginning of IC1 and International Smart Grid Action Network (ISGAN) collaboration on smart grids. While IC1 focuses on the development and demonstration of smart grid technologies, ISGAN, an IEA Technology Collaboration Programme (TCP) and Clean Energy Ministerial (CEM) Workstream, is active in later stages of the innovation spectrum, focusing on deployment and policy support. In Rome, representatives from the two international initiatives signed a Letter of Intent, formalizing joint collaboration and knowledge sharing on topics of mutual interest.

IC1 and ISGAN later held a joint workshop, the "1st CEM ISGAN/MI IC1 Forum to Facilitate Cooperation to Accelerate the Market Uptake of Smart Grids," on the margins of CEM10/MI-4 in May 2019 (Vancouver). Members released two factsheets (on Power System Flexibility and on Energy Storage Integration), which were the products of ongoing ISGAN-IC1 collaboration. The event also presented the opportunity to announce the SGIA Platform (see Project #3) and to award the best industry-led research and innovation projects on system flexibility.

IC1 and ISGAN are continuing joint work with the preparation of two additional factsheets on the topics of "mega versus micro grids" and "digitalization." Additional engagement will take place at the IC1 Task and ISGAN Annex levels.[4] These more targeted collaborations are expected to bring concrete outcomes in the coming years and will be the subject of a second letter of intent to be signed by the two initiatives.

[3] Beijing (June 2017), Delhi (November 2017), Malmö (May 2018), Rome (November 2018), Vancouver (May 2019), and Paris (November 2019).
[4] As noted above, IC1 has six R&D 'Tasks'. ISGAN has eight 'Annexes'.

Project #3: Smart Grids Innovation Accelerator

The Smart Grids Innovation Accelerator (SGIA) is a cloud-based online platform that will share knowledge on smart grids and the energy sector as a whole. By means of a powerful semantic search engine, the SGIA platform will allow advanced search functionalities on key documents selected and shared by IC1 members from the public and private sectors. Relevant documents to be included in the SGIA platform repository are national energy policies and strategies, roadmaps, position papers, technical reports, case studies, best practices, and videos on smart grids and related topics. The effective sharing of information, promoted by the SGIA, will enhance public-private collaboration toward the deployment of enabling technologies and new business models.

IC1 launched the first phase of Platform development at the 4th IC1 Deep-Dive Workshop in November 2018 in Rome and presented phase one outcomes at the 1st IC1-ISGAN joint event in May 2019 during CEM10/MI-4 in Vancouver. As of August 2020, the SGIA platform phase two is being finalized by a team of companies led by IBM. The SGIA platform will be supported by artificial intelligence (AI) algorithms to translate documents from different languages, provide a speech-to-text functionality for video and audio files, and have options to personalize users' search results and notes. IC1 aims to finalize a promotional video describing the SGIA main functionalities in September 2020 and to release the complete version of the SGIA platform in fall 2020.

Italy is leading this initiative and has contributed more than €240,000 in external contracts to support phase one and phase two development of the project. Long-term maintenance of the SGIA platform is expected to be managed by one or more IC1 countries.

IC1's Impact

Since its inception, IC1 has demonstrated the ability to leverage internal and external partnerships to accelerate smart grids innovation. IC1 members are active participants in the initiative and remain engaged through regularly scheduled teleconference calls, face-to-face meetings, and opportunities to shape joint products and activities.

Building on national experiences with domestic smart grids R&D programs, members have shared technical and policy expertise to advance key innovation priorities. Through India's Smart and Resilient Networks program, members are combining technical expertise and funding for smart grids R&D, collaborating on projects related to the integration of large-scale renewables in the conventional grid, electric vehicle infrastructure, finance and market strategies for the penetration of renewables, and cyber-physical systems in smart grids.

Meanwhile, the IC1-ISGAN collaboration helps to synchronize the R&D priorities and activities of two complementary initiatives and allows for a broader discussion on the full innovation spectrum for smart grid solutions. IC1 and ISGAN continue to develop joint products based on mutual strengths.

Lastly, the SGIA Platform consolidates expertise into a central repository with enhanced search functionalities. It is expected to facilitate knowledge sharing and connect subject-matter experts, thereby helping countries and the private sector learn from each other's experiences on smart grids development and deployment and reduce duplication of effort.

INNOVATION CHALLENGE #2 (IC2)

Off-Grid Access to Electricity

About IC2

Objective: "To develop systems that enable off-grid households and communities to access affordable and reliable renewable electricity."

Co-leads: France, India

Participants: Australia, Brazil, Canada, China, European Commission, Finland, Indonesia, Italy, Mexico, Netherlands, Norway, Republic of Korea, Saudi Arabia, Sweden, United Kingdom, United States

Remote communities not connected to large electricity grids often rely on aging diesel-powered generators; millions of people also rely on candles and kerosene for lamps. R&D is needed to bring down the cost of renewable electricity systems (e.g. solar photovoltaic technology, wind, small hydro) and to equip people and communities that do not have access to the electricity grid with renewable options. IC2 members are working to develop renewable systems that are cheaper than fossil fuels for affordable access to off-grid electricity.

Project #1: Stakeholder Meetings

IC2 held two international workshops on off-grid access to electricity. These workshops brought together policymakers, technical experts, industry representatives, and investors to discuss RD&D pathways to support off-grid solutions that benefit people living in marginal conditions. These forums also considered opportunities to strengthen IC2's relationships with international organizations.[5]

At the First International Meeting on Off-grid Access to Electricity on July 12, 2018 (Paris), IC2 members engaged stakeholders on innovation needs and opportunities for off-grid communities. The workshop was organized in collaboration with the IEA and gathered more than 100 stakeholders involved in off-grid access to electricity. Building on the first workshop, the Second International Meeting on Off-grid Access to Electricity on March 1-2, 2019 (Delhi) considered the entire value chain for off-grid solutions, including the technical, social, and economic dimensions of adapting clean energy opportunities to local contexts. The meeting was coupled with an exhibition to showcase successful off-grid solutions.

Project #2: Calls for Proposals to Support Off-Grid Demonstration Projects in Real-field Conditions

France and India, as co-leads of IC2, have funded 18 demonstration projects that seek to advance off-grid access to energy. Funding not only supports the testing of technologies in diverse geographic, climatic, and economic conditions – from energy storage in mountain communities to solar desalination

[5] Such as: the IEA, IRENA, WEF, United National Industrial Development Organization (UNIDO), Sustainable Energy for All (SE4ALL), the African Development Bank (ADB), International Solar Alliance (ISA), and Rocky Mountain Institute (RMI).

plants in coastal communities to pay-as-you-go meters for access to electricity in other rural applications – but it also supports the testing of business models adapted to relevant conditions.[6]

Projects were selected through two calls for proposals:

- France's call for proposals (€5.8 million) focused on access to energy in African countries. From 92 submissions, the French Agency for Ecological Transition (ADEME) selected nine projects.
- India's call for proposals (US$5.0 million) focused on off-grid projects in India, with funding recipients partnering with at least one other MI country to deliver on their projects.[7] India's Department of Science and Technology selected nine projects for funding.

The winners of both competitions were announced at MI-3 in May 2018 (Malmö). Since then, project leads have been developing and demonstrating their solutions, with the majority of projects expected to be complete by December 2020.

Building on the momentum of the first call for proposals, France launched a second round in 2019 to support innovative projects led by non-governmental organizations or enterprises in Africa through grants and technical assistance. With a budget of approximately €6.0 million, including France's contribution of €1.6 million, 80 project proposals were received and 10 projects were selected for funding. This second call for proposals targeted projects with large-scale deployment potential (nationwide and in neighbouring countries). Thanks to this grant, projects leaders should be able to mobilize more conventional financing and scale up their innovative energy access projects.

Project #3: Off-Grid Innovation Challenge Synthesis Report (2019)

IC2 sought to identify the major programmes, initiatives, collaborations, and success stories of participating countries in developing off-grid solutions. Released in March 2019 during the Mission Innovation Stakeholder Meeting on Off-grid Access to Electricity (Delhi), the Off-Grid Innovation Challenge: Synthesis Report-2019 summarizes the activities of 19 countries in advancing off-grid solutions.

The report provides briefs for each of the 18 off-grid demonstration projects supported by France and India as well as a summary of the programmes and strategies employed by MI countries in delivering affordable, high-performance access to energy in off-grid and remote communities. The document is expected to inform further collaboration between scientists, stakeholders, and organizations in MI countries who are working to develop and demonstrate affordable off-grid solutions. For example, researchers in Australia are building on IC2's findings to develop financial mechanisms that support off-grid electricity in developing economies.

[6] For a full list of projects, including project objectives and expected outcomes, refer to France's project report (https://www.ademe.fr/sites/default/files/assets/documents/off-grid-access-energy-010607.pdf) and India's project report (http://dst.gov.in/sites/default/files/Off-Grid-Brochure-23rd-May-2018.pdf).

[7] Specifically, project leads collaborated with researchers and non-governmental organizations from Australia, Canada, France, Germany, Italy, Norway, Sweden, UK, and US.

IC2's Impact

IC2 has contributed to MI's mission by supporting the development and demonstration of affordable clean energy solutions and business models for remote communities in various contexts. Through the Calls for Proposals for Off-Grid Demonstration Projects, IC2 co-leads helped to crowd in private sector interest and expertise from think tanks, international organizations, private investors, and researchers from around the world. In collaboration with various consortia, IC2's network and financial contributions have helped start-ups test and adapt energy solutions to the infrastructure, demographics, and energy resources available in an area. Such projects also enabled skills development and capacity building within communities. Projects are still ongoing; however, they are expected to result in reliable and more affordable energy solutions for remote households and communities.

IC2 has also enhanced collective knowledge and reinforced the research community around off-grid energy solutions, compiling insights into a synthesis report and convening government representatives and stakeholders at international meetings to share innovation priorities, success stories, and lessons learned.

INNOVATION CHALLENGE #3 (IC3)

Carbon Capture

About IC3

Objective: "To enable near-zero CO_2 emissions from power plants and carbon intensive industries."

Co-leads: Saudi Arabia, United Kingdom

Participants: Australia, Canada, China, Denmark, European Commission, Finland, France, Germany, India, Indonesia, Italy, Japan, Mexico, Netherlands, Norway, Republic of Korea, Sweden, United Arab Emirates, United States

Carbon Capture, Utilisation and Storage (CCUS) technologies are essential for achieving deep emission reductions across many industries (including in the power, cement, iron and steel, and chemicals sectors). CCUS is a proven technology, yet opportunities remain for improving performance, reducing capture cost, consolidating global storage capacity, and discovering new uses for CO_2. IC3 provides a platform for advancing international collaboration in CCUS research and development, unlocking the potential of CCUS and helping countries achieve their climate goals.

Project #1: CCUS Experts' Workshop

On September 26-28, 2017 (Houston, Texas), IC3 held an international workshop, bringing together approximately 250 experts selected from 21 countries to discuss CCUS technologies. Participants from all IC3 member nations, including attendees from governments, academic institutions (e.g. MIT and KAIST), and industry (e.g. Shell and Statoil), assessed the state of CCUS technologies, identifying knowledge gaps in materials design, transport phenomena, and economic evaluation. Delegates also identified the most promising directions for basic research to achieve long-term global carbon management objectives as well as opportunities for international R&D synergies.

After the workshop, IC3 published a comprehensive workshop report, "Accelerating Breakthrough Innovation in Carbon Capture, Utilization, and Storage," in May 2018. The report serves as a key resource for the international CCUS research community, governments, and the private sector, helping to inform national R&D policies and programs. Notably, workshop proceedings informed 28 priority research directions (PRDs) to inspire CCUS research and elucidate the foundational scientific phenomena that underpin CCUS technologies.

Project #2: Accelerating CCS Technologies (ACT) Call

In keeping with the CCUS PRDs identified at the Houston Workshop, IC3 members have worked with the European Commission's existing ACT Call, a funding platform for international collaboration in the CCUS space. Funding agencies within participating member countries are delivering these projects.[8]

[8] i.e. UK, USA, Norway, France, The Netherlands, Germany, Finland, Sweden, and Denmark – as well as non-MI members, such as Spain, Romania, and Turkey.

Specifically, IC3 is participating in the second ACT call (ACT2), which was launched in June 2018 with approximately €20.0 million for CCUS R&D projects. IC3 integrated its PRDs into ACT2 to ensure that CCUS R&D focuses on IC3-relevant areas. The call has brought 12 R&D projects to the fore – projects that aim to reduce costs, improve performance, and speed up large-scale deployment of CCUS technologies. These projects started to receive funding in September 2019; ACT2 will continue to fund projects up to 2022.

Due to the ongoing success of the initiative, IC3 is also participating in the third ACT call (ACT3), which was recently launched in June 2020. Participation in the initiative has also grown to 12 MI members, with India and Italy recently signing on to support the ACT3 call.

Project #3: High TRL CCUS Workshop

While the 2017 Houston workshop focused on early-stage research in CCUS, IC3 built on progress since 2017 and held a second workshop on June 19-20, 2019 (Trondheim, Norway) to identify research gaps, opportunities, and priorities in high TRL CCUS technologies. Convening 135 participants[9], the Trondheim Workshop sought to build working relationships between industry and research institutions around areas of common interest.

IC3 released a report in October 2019, distilling learnings from the Trondheim Workshop into recommendations across six CCUS topics: (1) decarbonizing industry sectors; (2) the role of CCS in enabling clean hydrogen; (3) storage and CO_2 networks; (4) storage monitoring; (5) going climate positive; and (6) CO_2 utilization. The report offers recommendations for the short, medium, and long term. Short-term recommendations (i.e. less than one year) included establishing joint initiatives and developing roadmaps. Medium-term recommendations (i.e. one to three years) included the creation of joint R&D projects, the launch of an international "Carbon Sink Project," and the potential use of AI and big data analysis for monitoring and storage. In the long term (i.e. greater than three years), delegates recommended implementing policy incentives to use low CO_2 value processes and products as well as engaging with financial communities to build confidence in CCUS. Recommendations have been incorporated into IC3's Action Plan.

IC3's Impact

IC3 workshops and corresponding reports have filled in knowledge gaps around technologies in the CCUS space, established new connections between industry and researchers, and reinforced strong working relationships between MI partners.

The Houston Workshop brought together experts from across sectors and resulted in a seminal report with 28 priority research directions for CCUS technologies. Accordingly, IC3 and stakeholders have helped actors around the world focus efforts on CCUS technologies with the potential to yield significant performance breakthroughs and cost reductions.

[9] Including IC3 members (Norway, Canada, The Netherlands, Germany, France, India, China, Australia, The Republic of Korea, Denmark, and Saudi Arabia), non-IC3 members (Switzerland and Poland), and industry players (including Total and Equinor).

Notably, these priority research directions have helped to inform how MI countries invest in CCUS R&D projects, with US$103.0 million in investments mobilized for collaborative R&D among MI countries and beyond. Indeed, many CCUS calls – particularly those related to international collaboration – are grounded in IC3's PRDs.

The ACT Platform has enabled active collaboration between MI countries on priority R&D areas. It provides a mechanism for countries to pool funding for critical CCUS research and helps to facilitate joint R&D projects by aligning aims and easing communication. The projects funded under ACT2 are in their early stages; however, successful projects are expected to deliver performance enhancements, cost reductions, and a greater understanding of IC3's PRD areas. Moreover, the ACT call has provided a means for IC3 to broaden its exposure and influence by guiding the CCUS activities of ACT nations.

Lastly, delegate recommendations from the Trondheim Workshop has initiated a broader discussion around high-TRL CCUS opportunities and the necessary actions moving forward.

INNOVATION CHALLENGE #4 (IC4)

Sustainable Biofuels

About IC4

Objective: "To develop ways to produce, at scale, widely affordable, advanced biofuels for transportation and industrial applications."

Co-leads: Brazil, Canada, China, India

Participants: Australia, Denmark, European Commission, Finland, France, Indonesia, Italy, Mexico, Netherlands, Norway, Sweden, United Kingdom, United States

Biofuels, in this context, are liquid or gaseous fuels made from biomass (e.g. biodiesel, bioethanol, renewable natural gas, and sustainable aviation fuels). They serve as renewable alternatives to fossil fuels in the transport and industrial sectors. While sustainable biofuels have an important role to play in reducing greenhouse gas emissions and improving the security of energy supply, many of the most exciting biofuels remain at the pre-commercial stage of development. IC4 members collaborate on biofuels RD&D in order to accelerate the rollout of sustainable biofuel solutions worldwide.

Project #1: Sustainable Biofuels Workshops

IC4 members organized a number of workshops related to sustainable biofuels. Objectives and outputs from a selection of workshops are described below:

- In November 2017 (Ottawa), IC4 and the IEA Renewable Energy Division jointly held the "Bioenergy for the Future Workshop." The more than 100 participants at this one-day event discussed lessons learned from previous attempts to scale up biofuels supply and conversion technologies.[10]
- On February 26-27, 2018 (New Delhi), India hosted the "1st International IC4 Conference on Sustainable Biofuels." Over 400 delegates from government, academia, and the private sector from 19 countries convened to take stock of progress on advancing the bioeconomy and to share best practices in scaling up sustainable biofuels. IC4 members and the Biofuture Platform signed the New Delhi Declaration at the event, formalizing an agreement to collaborate on sustainable biofuels research, development, demonstration, and deployment.
- On April 2-4, 2019 (Yantai), China hosted the "2nd International IC4 Conference on Sustainable Biofuels." More than 70 experts and scholars, including delegates from seven MI member countries, presented on technical research results, market development of biofuel industries, and national and international biofuel programs. Delegates also proposed ideas for how to advance the commercialization of sustainable biofuel technologies.
- On May 30-31, 2019 (Vancouver), Canada and the China-Canada Bioenergy Centre (C-CBC) jointly hosted the "Advanced Biofuels: Pathways to Market" Workshop, which focused on financial, policy, and technological barriers to the demonstration and large-scale supply of biological feedstocks. Participants also explored strategies for connecting stakeholders as well as

[10] Participants were from Canada, the U.S., the EU, Brazil, India, Netherlands, Sweden and New Zealand and IEA.

potential solutions to advance commercial scale production of biofuel technologies. Over 140 representatives from the biofuels industry, academia, and government attended the workshop.

Project #2: Sustainable Biofuels Reports

A key input for and output from many of IC4's workshops was the development of various reports on advanced biofuels. For example:

- IC4 members contributed to the IEA Technology Roadmap, "Delivering Sustainable Bioenergy," which was rolled out at the 2017 Bioenergy for the Future Workshop in Ottawa.
- IC4 and the Biofuture Platform collaborated on a multinational survey to assess the state of the bioeconomy in various countries. In 2018, findings were summarized in **"**Creating the Biofuture: A Report on the State of the Low Carbon Bioeconomy," along with a deeper look at the scale-up challenges for the sector ahead.
- Canada developed a survey and prepared a summary report, "Status of Advanced Biofuels Technologies and Innovation Gaps" as part of preparations for advanced biofuels discussion on the margins of the Fourth MI Ministerial.
- Canada, China, India, and Brazil developed reports summarizing the state of sustainable biofuels in their respective countries. The reports outline the status of each country's biomass resources, emerging biofuel technologies, national programs and best practices. The findings were presented at the May 2019 Pathways to Market Workshop in Vancouver. Following the same workshop, collective insights on ways to overcome barriers to scale-up were consolidated into a report, "Advanced BioFuels: Status and Scale-up Barriers."

Project #3: Coordination for Sustainable Biofuels R&D Funding

IC4 has used its convening power to promote funding opportunities for advanced biofuels RD&D and facilitate connections between funding bodies and researchers. For example:

- India launched a Funding Opportunity Announcement in 2018 worth US$5.0 million to support collaboration with academia, industry and Mission Innovation partners. India funded 14 projects under this initiative in the field of advanced biofuels, the production of enzymes for biofuels, and methods for improving biological feedstock and heterotrophic algal production. India provided funding for Indian researchers with the proviso that the work must include collaboration with researchers in IC4 countries.[11] Nine member countries[12] are involved in this three-year program.
- IC4 informed the development of a funding call under the EU's Horizon 2020 programme: "H2020 International cooperation with Canada on advanced biofuels and bioenergy." The call contributes to IC4 objectives and seeks to advance biomass supply chains and accelerate the deployment of advanced biofuels in the transport, power, and heating sectors. Planning discussions between the EU and IC4 members were held at many of IC4's workshops (described above). IC4 members also helped to bring together proponents from Canada and the EU for this programme.
- Building on trilateral collaboration on biojet fuels between Canada, the U.S., and Mexico, in August 2018, Canada launched the Sky's the Limit Challenge, a prize competition to fund innovation breakthroughs in sustainable aviation fuels. IC4 provided technical expertise and

[11] Researchers from outside of India are responsible for their own funding – although provisions have been made for site visits to Indian laboratories.
[12] i.e. Australia, Canada, China, France, Germany, Italy, Norway, UK, and USA.

coordination for the trilateral meetings and supported the launch of the prize competition by disseminating information on the program and convening researchers. The grand prize of CAN$5.0 million will be awarded to the top green aviation fuel consortium to help commercialize their winning biojet fuel.

IC4's Impact

In the relatively short timeframe of IC4, the challenge has had a major impact in promoting international networking and collaboration. IC4 has convened the international sustainable biofuels community (Project #1), bringing together government representatives, researchers, industry, and other key stakeholders to discuss information gaps, barriers to technology demonstration and scale-up, and opportunities for innovation and commercialization in the sustainable biofuels sector. IC4 has worked in close collaboration with the Biofuture Platform in particular, as both initiatives continue to align their respective efforts across the biofuels innovation spectrum to help realize the full potential of sustainable biofuels. Meanwhile, IC4-led reports (Project #2) consolidate findings and facilitate knowledge sharing within the advanced biofuels RD&D community.

IC4 contributed to the development of funding calls and provided a platform for countries to leverage financial resources with complementary international expertise (Project #3). The funding programs noted above were launched relatively recently and as a result, more time is needed before project leads can report conclusively on all outcomes. However, these funding projects have already helped to generate advances in biofuel technologies in the field of enzyme technology, second-generation ethanol demonstration, algal strain improvement, and sustainable aviation fuels. Lastly, momentum from IC4 has helped individual members to engage stakeholders and build strategic partnerships with other member countries, partners, and the private sector.

INNOVATION CHALLENGE #5 (IC5)

Converting Sunlight

About IC5

Objective: "To discover affordable ways to convert sunlight into storable solar fuels and/or solar chemical products."

Co-leads: European Commission, Germany

Participants: Australia, Brazil, Canada, Chile, China, Denmark, Finland, France, India, Italy, Japan, Mexico, Netherlands, Norway, Saudi Arabia, Sweden, United Arab Emirates, United Kingdom, United States

The potential contribution of solar energy to a clean energy future is not being fully exploited: sunlight can be used to produce carbon-neutral fuels (such as hydrogen) and develop energy storage chemicals. In other words, sunlight can be used to turn reactants (e.g. water, CO_2, nitrogen or metal oxides) into energy rich products like molecular hydrogen, methane, ammonia, or metals. IC5 members are working together on research and innovation related to solar fuel technologies and solar chemical products, an area where global collaborative activity is limited.[13]

Project #1: Cambridge Report

Building on insights gathered at the 6th Solar Fuels and Solar Cells Conference in October 2018 (Dalian, China), IC5 held a workshop with experts in March 2019 (Cambridge, UK) to validate priority areas of collaboration and research. Deliberations from that workshop ultimately informed the Cambridge Report, which was finalized in May 2019.

The report highlights the need for more cross-border collaboration on the research and development of sunlight conversion technologies and proposes a number of actions for IC5 to pursue, including the creation of networks, the development of global roadmap(s), the development of best practices for standardized comparison of results, and coordination with other Innovation Challenges and international initiatives. The report also summarizes priority areas for solar fuels RD&D, breaking priorities down further according to low, medium, and high TRL levels.

Combining insights and contributions from 17 experts from 10 countries[14], the Report guides IC5's actions and will continue to be used to inform post-2020 activities.

[13] IC5 identified six areas of focus: (1) Catalyst development for water splitting, CO_2 reduction and other key reactions; (2) Improved solar light-harvesting, charge separation and coupling to catalysts; (3) Cyanobacteria and micro-algae that excrete fuels or chemicals into a surrounding medium; (4) Photoelectrochemical, photocatalytic and hybrid bio/inorganic devices; (5) Thermochemical pathways using concentrated sunlight; and (6) Design, engineering and demonstration of devices and systems.

[14] Brazil, Canada, China, the EU, Finland, France, Germany, Italy, Netherlands, and Sweden contributed to the Report; additionally, experts from Australia, South Korea, and the US participated in the March 2019 workshop.

Project #2: IC5 Roadmap

In the Cambridge Report, IC5 noted that there is currently no global roadmap for solar fuels. In September 2019, IC5 began developing such a roadmap. Borrowing insights from existing roadmaps used in IC5 member countries[15] and related programmes and activities, the Global IC5 Roadmap is intended to define how IC5 members can collaboratively meet objectives and accelerate the development and deployment of solar fuel technologies.

The document is still under development. It will provide a vision for Solar Fuels and Solar Chemicals, with particular emphasis on the value chains for converting sunlight innovation, the conversion technologies themselves, and the integration of these new technologies into the energy system. The Roadmap will also take into account concepts associated with the Green and Circular Economy.

All IC5 member countries are involved in shaping the roadmap. Members have refined the roadmap through engagement with stakeholders, including through an IC5-organized workshop with European stakeholders in October 2019 (Brussels), followed by a second workshop in Japan in November 2019 (Hiroshima). A final workshop is planned for September 2020; it will be organised as an online workshop. IC5 expects the final roadmap will be complete by November 2020.

Project #3: Funding Solar Fuel Projects

IC5 defined a workplan in 2017 and one of the actions highlighted in that workplan was to organize a call for proposals with a cross-border focus. Funding has been targeted toward consortia of researchers and industry partners from MI member countries. These funding programs include two calls for proposals and one inducement prize:

- India held a US$6.0 million call for proposals for joint R&D with six MI member countries in the field of Converting Sunlight. The funding opportunity supports the discovery of scalable, non-toxic materials and processes to convert sunlight into storable fuels and promotes international collaboration on R&D in this area. This initiative is financing 13 research projects, all of which are still ongoing and all of which require the participation of a representative from at least one MI member country.[16]
- Under Horizon 2020, the European Union held a call for proposals on "Converting Sunlight to Storage Chemical Energy." The funding opportunity is designed around IC5's objectives to replace fossil energy with sustainable solar fuels that provide the same flexibility and convenience of use. The call included a requirement to include at least one non-EU MI member in the proposed consortium; nine MI members are participating in the call along with other EU countries.[17] The call for proposals closed on August 27, 2019. Two research projects are funded under this initiative and are ongoing, with the EU contributing €6.0 million and non-EU partners contributing €1.0 million – a total of €7.0 million for these projects.

[15] In particular, the roadmap builds on insights gleaned from the EU's SUNRISE project, recent projects in Japan, and the US roadmap.

[16] Funding aims to advance the design of: plasmonic nanomaterials for conversation of CO_2 to methane; development of 3D printed porous covalent organic frameworks (COFs); design and synthesis of heterojunction photocatalysts; hybrid organic-inorganic perovskite materials and catalysts for solid oxide electrochemical cells (SOEC) for conversation of CO_2 to CO.

[17] The MI countries participating are China, Denmark, France, Italy, Japan, The Netherlands, Sweden, United Kingdom, and United States.

- In December 2017, the European Commission launched its Prize for Artificial Photosynthesis at the One Planet Summit in Paris. Contestants from around the world are competing for a €5.0 million prize by building a prototype that artificially recreates the photosynthesis process to produce synthetic fuel. The prototype needs to integrate the whole photosynthesis process, from light capture to fuel production, with the fuel being capable of powering a small engine. The deadline for submitting applications for the inducement prize is February 3, 2021, with the final prize awarded by the end of 2021. IC5 expertise was instrumental in defining the terms of the prize.

IC5's Impact

IC5 has established an international network of experts in the area of converting sunlight into solar fuels, including researchers, engineers, and industry representatives. Previously, there was limited international collaboration in this area. These efforts have helped to raise awareness about the challenges and potential for solar fuel technologies. Moreover, through the Cambridge Workshop, IC5 convened the international research community on solar fuels, with the ensuing Cambridge Report elaborating on priority actions and areas of research. The IC5 Roadmap for solar fuels builds on this work, providing a unified, global vision for these technologies and mapping out value chains and the integration of conversion technologies in greater detail.

IC5 members have also been working together on funding opportunities for solar fuels research and development. As part of the three funding opportunities noted above, IC5 member countries have invested approximately US$18.0 million (€16.5 million) since 2017 in solar fuels. Cross-border partnerships was a feature – and in some cases, a requirement – of these funding calls, further reinforcing global networks and information sharing.

INNOVATION CHALLENGE #6 (IC6)

Clean Energy Materials

About IC6

Objective: "To accelerate the exploration, discovery and use of new high-performance, low-cost clean energy materials."

Co-leads: Canada

Participants: Australia, Denmark, European Commission, Finland, France, Germany, India, Italy, Mexico, Norway, Republic of Korea, Saudi Arabia, Sweden, United Kingdom, United States

Materials discovery is a key factor in the development of new energy technologies. IC6 aims to accelerate the innovation process for high-performance, low-cost clean energy materials across a range of energy sectors and applications. For example, new materials can benefit the development of advanced batteries and solar cells, low-energy semiconductors, thermal storage, structural materials, and catalysts for the production of hydrogen or conversion of carbon dioxide.

Project #1: Clean Energy Materials Workshops

Over the past four years, IC6 has connected government officials, industry leaders, and technical experts in the field of clean energy materials. Among the many events hosted by members, a selection of key workshops are highlighted below.

- On September 11-14, 2017 (Mexico City), IC6 hosted its first international expert workshop, with 133 participants from 18 MI members. The participants convened to understand the state of the art in materials discovery, present the urgent need for a materials revolution, and elaborate on six grand goals to enable accelerated materials discovery and development. Participants conceived the development of materials acceleration platforms (MAPs) – that is, autonomous laboratories that can accelerate the discovery of clean energy materials by at least a factor of 10. Proceedings from the workshop were summarized in an expert report, "Materials Acceleration Platforms," which was published in January 2018.[18] Ultimately, the expert workshop and report provided a scientific roadmap for IC6 to follow and defined the strategic direction of the Innovation Challenge.
- Building on the first event, IC6 hosted the "Structural Materials and 3D Printing Workshop" on March 15-16, 2018 (Hamilton). It focused on the state of advanced materials for clean energy technologies, the significance of structural materials like cement and steel, and promising R&D directions.
- IC6 engaged researchers and industry leaders at subsequent events, looking at ways to deepen collaboration with these stakeholders. The workshop on "Self-driving Materials Laboratories: The Next Paradigm for Accelerated Discovery" (May 9, 2018, Toronto), elevated the vision of IC6

[18] The report was co-authored by 33 experts from more than 10 countries. It was followed by a paper published in the journal, *Nature*, in April 2018: "Accelerating the discovery of materials for clean energy in the era of smart automation."

among key industry members. "IC6 Business Day" (May 22, 2018, Malmö) and the "IC6 European Meeting" (October 25, 2018, Rome) also offered opportunities to engage academics and industry on materials R&D that could support various clean energy applications in the future.

Project #2: Advancing Materials Acceleration Platforms

IC6's flagship project has been the advancement of MAPs. Traditionally, the development and deployment of new materials is a costly and risky process, requiring 10-20 years to generate results. By using AI, MAPs allow scientists to produce new materials based on desired properties on a shortened timescale. As a result, MAPs could transform the energy sector, helping to boost the performance of clean energy technologies and/or make them more cost competitive.

In November 2018, Canada, as co-lead of IC6, announced a CAN$8.0 million investment in a MAP project, the *Autonomous Discovery Accelerator* (Project Ada) at the University of British Columbia. Project Ada is a first-of-its-kind toolkit that uses AI, smart robotics, and high-performance computing to accelerate the discovery and development of materials. Presently, project leads are using Project Ada to develop and optimize materials for two different applications: (1) advanced solar cells, and (2) CO_2 conversion. Positive proof-of-concept preliminary results have been published, demonstrating the functional ability of MAPs to repeatedly converge on an optimized material formulation.[19]

Project Ada inspired Canada to develop additional MAPs.[20] As of March 2020, Canada has invested CAN$14.0 million in MAPs. Meanwhile, IC6 continues to serve as a venue for high MAP-potential countries to pursue multi-lateral projects with each other.

Project #3: Collaboration with other Innovation Challenges

Materials make up more than 50% of the cost of clean energy solutions – including those used in renewable energy production, use, and storage. Consistent with the findings of the January 2018 expert report, IC6 has actively engaged other Innovation Challenges, offering to collaborate on advanced materials for a variety of technology applications.

For example, IC6 rallied the co-leads and scientific community associated with MI's Innovation Challenge on Affordable Heating and Cooling of Buildings (IC7). A series of IC6/IC7 workshops were organized[21] to discuss innovation priorities for the heating and cooling of buildings as well as the potential for MAPs to advance R&D efforts. IC6 and IC7 co-developed a workflow for a thermal energy storage MAP – one that will accelerate the discovery and development of low-cost thermal energy storage materials for the heating, ventilation, and air conditioning (HVAC) building technologies of the future.

IC6 has also reached out to IC3, IC5, and IC8, which have strong materials dependencies. Discussions are ongoing regarding how IC6 can best support other Innovation Challenges with their work.

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[19] For more information, see MacLeod et al. (2019). "Self-driving Laboratory for Accelerated Discovery of Thin-Film Materials." *Science Advances*.

[20] Specifically, Canada is developing: (a) A Thermoelectric Generator MAP, which will focus on developing low-cost, environmentally friendly materials for the conversion of waste heat to electricity; (b) An Electrocatalyst MAP, which will support the development of catalyst materials for hydrogen production and CO_2 conversion to fuels; and (c) A 3D Printing MAP, which will explore the entire additive manufacturing value chain.

[21] Workshops were held in April 2019 (Ottawa), June 2019 (Brussels), and November 2019 (Erlangen).

IC6's Impact

When MI was formed, there were no collaborative initiatives on the topic of clean energy materials on an international scale. IC6 filled that gap.

Through workshops, IC6 introduced MAPs, not only promoting capacity building within government research communities, but also demonstrating to IC6 member states how sustainable materials can directly support regional needs and accelerate the transition to a low-carbon economy. Collective wisdom gathered through workshops has also helped IC6 to identify high-impact opportunities for R&D and collaboration on materials innovation (e.g. hydrogen-powered steel production, CO_2 conversion to value-added products, cement formulation, and thermal energy conversion). In particular, the September 2017 workshop and the ensuing expert report provided a vision for how MAPs can be brought into existence and offered guiding principles for how IC6 could engage key stakeholders – including, how to support other Innovation Challenges with their materials science problems.

IC6 is also contributing to MI's mission by supporting technological breakthroughs in materials science. By advancing MAPs, IC6 members are supporting a revolutionary way of conducting science, as researchers seek to discover and develop materials for near-term commercialization *and* optimize the MAPs themselves for replication and use in other settings. Project Ada, for example, has demonstrated that it is possible to accelerate clean energy materials discovery through MAP technology.

Additionally, IC6 has initiated new, cross-border discussions with four other Innovation Challenges. Ultimately, these engagement efforts support MI's mission to accelerate the pace of clean energy innovation by combining complementary networks and areas of expertise. With further time and investment, collaboration between IC6 and other Innovation Challenges could support performance breakthroughs and/or cost reductions in a variety of sectors (including

INNOVATION CHALLENGE #7 (IC7)

Affordable Heating and Cooling of Buildings

About IC7

Objective: "To make low-carbon heating and cooling affordable for everyone."

Co-leads: European Commission, United Arab Emirates, United Kingdom

Participants: Australia, Austria, Brazil, Canada, China, Denmark, Finland, France, Germany, India, Italy, Mexico, Netherlands, Norway, Republic of Korea, Saudi Arabia, Sweden, United States

Mainstream technologies for the heating and cooling of buildings tend to be energy intensive: globally, buildings account for almost a third of final energy consumption, with space heating and cooling and the provision of hot water accounting for approximately half of this consumption. IC7 seeks to support the development of heating and cooling solutions that will massively reduce energy use and carbon emissions.[22]

Project #1: Global Cooling Prize

Room air conditioners are estimated to contribute over 132 gigatons of CO_2 emissions from now until 2050 and could contribute over 0.5°C of warming by 2100.[23] The Global Cooling Prize (GCP) is a US$3.0 million competition that seeks to stimulate innovation in the cooling space. Funding directly supports the development of cooling technologies with the potential for five times less climate impact than market offerings – at no more than two times the first investment cost.

Applications opened globally in 2018. Out of the 139 technical applications received from 31 countries, eight finalists were selected in November 2019. Finalists are developing and testing their prototypes for performance in the lab and in real-world conditions in India. Having received US$200,000 to build a demonstrator, finalists are competing for the ultimate prize of US$1.0 million, with the winner announced at an award ceremony in March 2021. The solutions will also inform a Cooling Roadmap for Cities – a collaborative project between IC7, the Global Covenant of Mayors (GCoM), and the UN's Cool Coalition.

The initiative is jointly led by India's Department of Science and Technology, the Rocky Mountain Institute (RMI), and IC7 and benefits from the support of government departments, industry leaders, and international organizations.[24] IC7 has provided organizational and promotional support for the

[22] IC7 has prioritized six technology areas for research and innovation (1) Thermal Energy Storage; (2) Heat Pumps; (3) Non-atmospheric Heat Sinks/Sources; (4) Predictive Maintenance and Control Optimization (5) Thermal Comfort and (6) Building-level Integration. Refer to IC7's webpage for more information about these priority areas: http://mission-innovation.net/our-work/innovation-challenges/affordable-heating-and-cooling-of-buildings/

[23] See Campbell et al. (2018). "Solving the Global Cooling Challenge: How to Counter the Climate Threat from Room Air Conditioners." Rocky Mountain Institute.

[24] A full list of partners for this initiative can be found on the GCP website.

initiative, with India, as a member of IC7, providing a significant proportion of funding for the prize. Other core funding for the prize has come from philanthropic sources.

The prize engages private sector industry participants:

1) As participants in the prize competition, with companies like Daikin, Gree, Haier, Godrej as finalists, and
2) In the investor marketplace, where consenting participants and potential investors are connected. Here, a number of leading companies pay a modest fee ($50K) for participation and in return share curated information and analysis on submitted technologies from consenting prize participants under the protection of the prize nondisclosure, non-use and confidentiality agreements.

Project #2: Comfort and Climate Box (CCB)

IC7, in collaboration with two IEA TCPs,[25] initially conceptualized the Comfort and Climate Box during the first IC7 Workshop in November 2017 (Abu Dhabi). An innovative concept to improve energy efficiency in buildings, the CCB integrates heating, cooling, and energy storage solutions into a compact and multifunctional device, compatible with a smart energy grid. Not only would the CCB be able to receive multiple energy inputs, but it would also use and store energy to meet heating, cooling, and power demands in an optimized fashion – whether the objective is to provide heating and cooling for a building at the lowest cost, with the lowest impact on the electricity grid, or in a way that generates the lowest amount of CO_2.

10 MI members are actively working together to accelerate the market development of Comfort and Climate Box solutions.[26] Cooperation between specialists from various technology areas is required, given the challenge of combining multiple technologies into one compact system. Not only is IC7 working with IEA TCPs, but it is also working with research organizations and industry to accelerate product development and market introduction of CCBs.

The collaboration is task shared,[27] with national governments sourcing funding for CCB-related projects in their respective countries. Based on the number of partners and IEA rules for contributions per project, collective funding for CCBs is estimated at £3.0 million. A managing agent has been employed to help coordinate the project. Participating countries are delivering on different aspects of this work and developing CCB solutions to meet local needs. IC7 members are also sharing lessons learned from their local experiences.

This project is ongoing. Beginning with a start-up workshop in January 2019 (Utrecht) to further define the project, IC7 members and partners have since secured funding and engaged stakeholders. Over the two-and-a-half-year timeline for this project, participants anticipate developing a market status report, developing and testing prototypes, and producing a roadmap with recommendations to manufacturers,

[25] The IEA TCPs involved in this initiative include: The Heat Pumping Technology TCP and the Energy Storage TCP.
[26] MI members involved in the CCB include: Austria, Canada, China, France, Germany, Italy, Netherlands, Sweden, UK and USA. Three non-MI countries are also involved in project activities (i.e. Belgium, Switzerland, and Turkey).
[27] The successful task shared model with the IEA is being used for another IC7 project: investigating predictive maintenance and control optimization with large-scale carbon saving potential, in which nine IC7 countries are involved.

policymakers, and standardization organizations. Ultimately, IC7 members seek to develop nearly market-ready systems, including, as a minimum, a heat pump and a storage system for CCB solutions.

Project #3: COMBIOTES (Compact Bio-Based Thermal Energy Storage for Buildings) – a Horizon 2020 Project

IC7 has secured funding for its work on thermal energy storage (TES) innovation under the EU's Horizon 2020 programme. Specifically, funding supports the COMBIOTES project, which seeks to develop and test a compact energy storage solution for domestic heating, hot water, and cooling, fully adapted for electricity load shifting – in other words, a device that would help shift electricity consumption for heating and cooling needs from one time period to another.[28]

The COMBIOTES project includes organizations based in both EU and non-EU MI member countries: coordinated by France's Commissariat à l'énergie atomique et aux énergie alternatives (CEA), and with the active involvement of two partner organizations from China (i.e. The Institute of Electrical Engineering of the Chinese Academy of Sciences and The Henan Province Guoan Heating Equipment Co.), EU members and China are working together to advance TES solutions. The project also brings together key players in energy storage and management, including researchers working on development and testing, small- and medium-sized enterprises focused on manufacturing and commercialization, and consumer and end-user representatives, such as building owners and operators.

With a budget of €4.0 million (funded by the EU and China), IC7 launched the COMBIOTES project on November 1, 2019, with the first phase of activities focused on specifications and requirements for the COMBIOTES system. Over four years, the project will develop prototypes and demonstrate TES solutions. Researchers are working toward an energy storage density greater than 100 kWh/m^3 for these prototypes.[29] This significant performance improvement would facilitate the development of compact systems for electricity load shifting, which in turn, would be easier to access and install in buildings.

IC7's Impact

These three projects are still ongoing; however, IC7 anticipates that they will yield performance breakthroughs that will enable more efficient and sustainable building systems, including:

- Disruptive technologies that can drastically cut cooling emissions with limited cost increases (Global Cooling Prize);
- Multifunctional devices that integrate varied energy inputs and optimize energy use for desired performance (Comfort and Climate Box); and
- A compact, easy-to-install, and energy efficient system to store thermal energy (COMBIOTES).

In the case of the Global Cooling Prize, between the 139 applications and eight funded demonstrations, IC7 and partners have brought to the fore a number of opportunities to develop concepts and create commercial solutions.

[28] "A first modular TES will be able to store hot tap water to be converted into ice storage during summer (cooling needs). A second compact [TES]…will store high heating energy amount, for space heating or hot tap water demands." Further technical details about this project are available on the Horizon 2020 website.
[29] In particular, the high volumetric energy density of a latent TES using a bio-based phase-change material (PCM) is one of the most novel innovations of the project, supporting energy storage capacity.

IC7 has played a strong convening role to support these three projects, bringing countries and partners together around specific performance objectives. With the Global Cooling Prize, IC7 and partners have galvanized the cooling industry and raised the public profile of low-carbon and affordable cooling solutions through a targeted media campaign and high-profile support from Sir Richard Branson. Meanwhile, the COMBIOTES project illustrates how IC7 member countries are collaborating on thermal energy storage solutions through the Horizon 2020 platform. Likewise, the Comfort and Climate Box initiative combines specialties from different countries and across different platforms (i.e. MI and IEA). In the course of its activities, IC7 has also developed a programme for endorsing complementary activities. By working together and with external stakeholders, IC7 members are enhancing collective knowledge and leveraging significant activity around research its priorities.

Finally, IC7 has enabled multilateral member engagement in identifying impact areas and strategic research collaborations. A number of member countries have structured their research programmes around Mission Innovation themes. Hence, MI is affecting the direction of innovation travel in these countries. For instance, it has resulted in new national and international programmes on energy demand reduction launched by India with funding to the tune of over US$30.0 million. India has established a dedicated MI IC7 resource unit that coordinates with all stakeholders among MI member countries, manages and coordinates IC7 initiatives, performs scientific and technical analysis in IC7 priority areas, and disseminates technical information. This has enabled India to accelerate research on IC7 priority areas both nationally and internationally through deep dives and strategic roadmaps to provide affordable comfort for all at minimum energy and emissions.

INNOVATION CHALLENGE #8 (IC8)

Renewable and Clean Hydrogen

About IC8

Objective: "To accelerate the development of a global hydrogen market by identifying and overcoming key technology barriers to the production, distribution, storage, and use of hydrogen at gigawatt scale."

Co-leads: Australia, European Commission, Germany

Participants: Austria, Canada, Chile, China, France, India, Italy, Japan, Netherlands, Norway, Republic of Korea, Saudi Arabia, United Kingdom, United States

Governments recognize the potential of hydrogen to reduce emissions, improve energy security, and enhance the resilience of the global energy system. For government policies around hydrogen to succeed and for hydrogen to reach its full potential, further technological improvements and greater market volumes are needed along the hydrogen value chain to make it cost-competitive in the broader energy system. IC8 provides a platform to identify and collaborate on the essential breakthroughs in hydrogen innovation.[30]

Project #1: Hydrogen Valleys Global Collaboration Platform

A "hydrogen valley" is a geographic area (e.g. a city, region, or industrial cluster) where several hydrogen applications are combined into an integrated hydrogen ecosystem.[31] Many demonstration projects have successfully shown the maturity and benefits of individual hydrogen technologies; however, the potential of hydrogen as an integrated, systemic solution has not yet been proven at scale.

There is no one-size-fits-all solution when it comes to hydrogen valleys: different countries have different infrastructure and economic, geopolitical, and environmental circumstances. To facilitate knowledge sharing and reinforce global alliances around hydrogen valleys, IC8 is developing an online information-sharing platform on hydrogen valley projects in MI countries. Information will be publicly available, but the platform will also allow contributing partners to take up direct contact with each other to share more detailed reflections on best practices and challenges.

IC8 members anticipate that the platform will be operational by December 2020, with the ensuing months (i.e. up until June 2021) used to fine-tune the platform. The European Union (via the European Commission) is initially financing the platform with a €500,000 contract through its Fuel Cells and Hydrogen Joint Undertaking programme while Germany and Australia are providing project support. IC8 member countries are contributing content related to hydrogen valley projects, including best practices

[30] IC8 has identified three priority areas for collaboration: (1) Hydrogen Valleys; (2) Hydrogen in the Gas Grid; and (3) Heavy Duty Fleets.

[31] Hydrogen valleys should ideally cover the entire hydrogen value chain: production, storage, distribution, and final use. As such, hydrogen valleys offer a pathway for scaling up and making hydrogen technologies more viable.

and case studies around value chain coverage, technology deployment, business models, regulatory environment and permitting procedures, project governance, budget characteristics and more.

Project #2: Hydrogen in the Gas Grid Working Group

The market deployment of hydrogen technologies requires transmission and distribution infrastructure. IC8 has noted that high capacity pipelines are likely the cheapest option for transporting hydrogen and can accelerate market deployment by leveraging existing infrastructure. In 2019, IC8 and the International Partnerships for Hydrogen and Fuel Cells in the Economy (IPHE) jointly set up a working group to address technical and regulatory barriers associated with hydrogen in the natural gas grid. In doing so, IC8 seeks to enhance information sharing, coordinate stakeholder efforts, and raise awareness among policy makers about the potential for using the gas grid for the transportation and storage of hydrogen.

The working group is mainly led by IC8 co-leads, the IPHE Steering Group, and the IPHE Regulations, Codes, and Standards Working Group. The broader IC8 and IPHE membership as well as relevant industry and research stakeholders were involved in an inaugural joint workshop on November 28-29, 2019 (Chester, UK). Participants discussed opportunities and challenges for blending hydrogen in the gas grid as a short-term option as well as medium- and long-term options for dedicated hydrogen pipelines. Workshop proceedings were summarized in a report, the findings from which have helped to inform priority areas of focus for the Working Group.

Based on the outcomes of the workshop, IC8 is developing an information-sharing mechanism by Q3 2020 that will map existing projects, studies, regulations, and codes/standards and describe best practices and opportunities for collaboration. Findings will be rolled up into a report and plan for collaboration by the end of 2020.

IC8's Impact

As a newer Innovation Challenge, launched in May 2018, IC8 has scaled up its activities in relatively short order. A number of international initiatives around hydrogen exist; however, IC8 has worked with stakeholders and partner organizations to identify areas where IC8 can generate the most impact in the short term.

IC8 is consolidating information on the latest technologies, lessons learned, and opportunities for collaboration related to the demonstration of integrated hydrogen solutions and infrastructure and distribution for hydrogen. For example, given that there are a limited number of research facilities that can conduct pressurized hydrogen testing for transport via pipelines, linking these laboratories to coordinate test conditions and sharing findings could help avoid duplication and accelerate deployment. In this way, IC8 members and partners are combining complementary areas of expertise to fill information gaps and reduce duplication of effort through the IC8 platform. The development of the Hydrogen Valley Global Collaboration Platform and the work of the Hydrogen in the Gas-Grid Working Group are still in progress, but these initiatives are expected to support policymakers, industry stakeholders, and the hydrogen RD&D community in developing roadmaps, reducing the costs of implementation, accelerating future project delivery, and driving replicability.

REFLECTION

Summary of Impacts

MI's eight Innovation Challenges have delivered on – and continue to deliver on – a variety of projects, including:

- Funding calls and prize competitions
- Information sharing platforms
- Formal collaborations with other organizations
- Workshops, reports, and roadmaps
- The contribution of technical and policy expertise to advance innovative solutions

Ultimately, a number of developments in the clean energy RD&D space would not have happened without MI's eight Innovation Challenges. The ICs have enabled MI members to:

1) **Strengthen international clean energy RD&D networks:** Despite differences in system structure, energy mix, and market structure, technology trends are global. Through the various projects described in this report, it is clear that all ICs have facilitated connections between researchers, industry, academia, think tanks, and other organizations around the world. Critically, ICs also bring policymakers to the table. Open dialogue between the research and policy communities can thereby help to inform national innovation priorities and investments. Developed over the course of MI's initial mandate, IC networks in and of themselves are a valuable resource for enhancing collective knowledge on various technology areas and for countries to learn from each others' experiences in advancing clean energy RD&D.

2) **Facilitate knowledge exchange:** Although the benefits of exchanging information and best practices between peers is not easily quantifiable, ICs recognize that bringing together complementary skills and expertise through events and day-to-day IC operations enables members to achieve more and to find creative solutions to problems. Findings have been captured in numerous workshop reports, country reports, and roadmaps. As well, information sharing platforms, such as IC1's SGIA and IC8's Global Hydrogen Valleys Platform, promote replication of successful strategies and ideas. Meanwhile, IC6 outreach to other ICs helps to support the material needs (and potential performance breakthroughs) in other clean energy technology areas. From this information exchange, members can then identify collaboration opportunities, borrow lessons learned from other contexts, and reduce duplication of efforts.

3) **Identify and inform global clean energy innovation priorities:** All ICs have advanced the conversation on innovation gaps and priorities for clean energy RD&D. Through IC1, IC2, and IC4 workshops on innovation needs and best practices, IC3's Priority Research Directions, IC5's Roadmap, IC6's Expert Report on Materials Acceleration Platforms, IC7's Cooling Roadmap for Cities, and IC8's Hydrogen in the Gas Grid Working Group – to name a few examples – ICs have informed strategies for stakeholder engagement, priorities for international collaboration, and recommendations for the future scale-up of technologies. Moreover, given MI's unique position in convening technical experts and policy makers, the innovation priorities that ICs identify can also inform national investments.

4) **Deliver on new collaborative projects:** By pooling financial resources and by bringing together experts from around the world, ICs are helping to build capacity, reduce duplication of effort, and drive RD&D in their respective areas. IC members do so by investing in clean energy projects – for example, through IC2's off-grid demonstration projects and India's IC1, IC4, and IC5 funding calls. ICs have also helped to crowd in additional funding from the private sector (e.g. IC7's Global Cooling Prize) and from MI members (e.g. via IC3's engagement with the ACT2 and ACT3 funding calls) to advance clean energy priorities.

5) **Fill gaps in the international clean energy ecosystem:** For example, IC6 offers a novel platform to collaborate on clean energy materials while IC5 has established a new international network of experts for solar fuel technologies. Both address areas where global collaboration was previously limited. As well, the work of ICs on RD&D often complements the work of deployment- and policy-related initiatives, as made evident through close collaboration between IC1 and ISGAN, IC4 and the Biofuture Platform, and IC7 and IEA TCPs.

While the projects identified throughout this report and in the summary above are not intended to be an exhaustive account of all IC activities and contributions, they do illustrate the multifaceted ways that ICs have supported Mission Innovation efforts to accelerate clean energy innovation.

ANNEX 1: Innovation Challenge Leads and Members

	Australia	Austria	Brazil	Canada	Chile	China	Denmark	European Union	Finland	France	Germany	India	Indonesia	Italy	Japan	Mexico	Morocco	Netherlands	Norway	Republic of Korea	Saudi Arabia	Sweden	United Arab Emirates	United Kingdom	United States
IC1 Smart Grids																									
IC2 Off-grid Access to Electricity																									
IC3 Carbon Capture																									
IC4 Sustainable Biofuels																									
IC5 Converting Sunlight																									
IC6 Clean Energy Materials																									
IC7 Affordable Heating & Cooling of Buildings																									
IC8 Renewable and Clean Hydrogen																									

Lead Participant